Modeling Wind Wave Evolution from Deep to Shallow Water

Tim T. Janssen

Theiss Research, PO Box 1533, El Granada, CA 94018
t: 415 609 5359 e: ttjanssen@gmail.com

Thomas H. C. Herbers

Department of Oceanography, Code OC/He, Naval Postgraduate School
Monterey, California 93943
t: 831 656 2917; f: 831 656 2712; e: thherber@nps.edu

Gerbrant Ph. van Vledder

Department of Civil Engineering and Geosciences, Delft University of Technology
2600 GA Delft, The Netherlands
t: +1 31 15 2781953 ; f: +1 31 15 2784842 ; e: g.p.vanvledder@tudelft.nl

Award: N000141310055, N0001413WX10002, N000141010391

LONG-TERM GOALS

Ocean waves are an important aspect of upper ocean dynamics, in particular on the shallow continental shelves and in coastal areas. The long-term objective of this work is to advance modeling capability in such coastal areas by improving model representations of effects associated with nonlinearity, inhomogeneity, and dissipation.

OBJECTIVES

The specific objectives of the present work are 1) to develop and implement an efficient and scalable approximation for the nonlinear quadruplet source term, 2) to develop and implement a generalized nonlinear source term that is accurate in water of arbitrary depth, 3) to develop and implement an improved nonlinear closure for triad nonlinear interactions in shallow water, and 4) improve representations of dissipation by wave breaking and wave-bottom interactions in shoaling waves.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2013**	2. REPORT TYPE	3. DATES COVERED **00-00-2013 to 00-00-2013**

4. TITLE AND SUBTITLE **Modeling Wind Wave Evolution from Deep to Shallow Water**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Theiss Research,PO Box 1533,El Granada,CA,94018**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**11**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

APPROACH

Modern, third-generation (3G) wave models are based on an action balance (or radiative transfer) equation, which describes the transport of wave energy (or action) through a slowly varying medium and time. In Lagrangian form (for convenience) this balance equation can be written as

$$\frac{dN(\mathbf{k})}{dt} = S_{in}(\mathbf{k}) + S_{ds}(\mathbf{k}) + S_{sc}(\mathbf{k}) + S_{nl}(\mathbf{k}) \qquad (1)$$

where $N(\mathbf{k})$ is the wave action at wavenumber vector $\mathbf{k}$ and t is time. The forcing terms on the right-hand side are referred to as source terms and account for the input of energy by the wind (S_{in}), spectral redistribution of energy through scattering by seafloor topography (S_{sc}) or through nonlinear wave-wave interactions (S_{nl}) , and dissipation of wave energy (S_{ds}) through e.g. breaking or bottom friction.

In this study we will develop and improve the source terms for nonlinear interactions S_{nl} and energy dissipation S_{ds}, to account for effects of finite depth and shallow water, and to ensure a consistent and smooth model representation of wave evolution from deep to shallow water.

Nonlinearity

We will develop an efficient method for the evaluation of the nonlinear source term, allowing for greater efficiency and accuracy in operational use. To allow modeling of wave propagation from deep to shallow water, we will modify the nonlinear source term to account for changes in relative water depth [Janssen *et al.* 2006], and develop an improved closure approximation for nearshore wave propagation [Janssen, 2006].

Dissipation

We will develop and test improvements to wave dissipation parameterizations through detailed comparisons of model results to laboratory and field observations in a wide range of conditions.

Field data

We will analyze, prepare, and disseminate selected field experimental data sets, collected by the PI's, to the project teams for the purpose of validation and calibration of new model developments.

WORK COMPLETED

Development of a Lumped Quadruplet Approximation (LQA)

A scalable parameterization of non-linear four-wave interactions is being developed to bridge the gap between time consuming exact methods and the fast but inaccurate Discrete Interaction Approximation (DIA). The focus in this work is on developing a consistent approximation of the complete interaction manifold based on the WRT method. We follow two main lines of development for achieving this.

First we improve numerical efficiency and limit the integration space by applying higher-order integration methods, filtering methods, simplified interpolation procedures, and re-sampling of points on the locus

Second is the Lumped Quadruplet Approximation (LQA), in which discrete contributions on the locus are treated as individual wave number configurations, which can be handled by the Generalized Multiple DIA Approaches (see e.g. Van Vledder, 2001; Tolman, 2012). Using this technique, various optimized sets of wave number configurations can be derived.

We are working toward three main approaches to evaluate the exact four-wave interactions: 1) the WRT method as implemented by Resio and Perrie, and Van Vledder, 2) Masuda's method implemented in the RIAM method by Komatsu, and 3) the method of Lavrenov implemented as the GQM by Benoit and Gagnaire-Renou (see e.g. Van Vledder, 2012). Although each of these methods aims to solve the same integral, it is not clear if they actually produce the same answers. This study is done in collaboration with Drs Hashimoto (RIAM) and Benoit (GQM).

Analysis and dissemination field observations.

We have disseminated several datasets to the NOPP teams. In particular, we have made available the ONR NCEX (Nearshore Canyon Experiment) field observations, which are particularly well suited to validate model representation of refraction and wave focusing over extreme topography (see Figure 1).

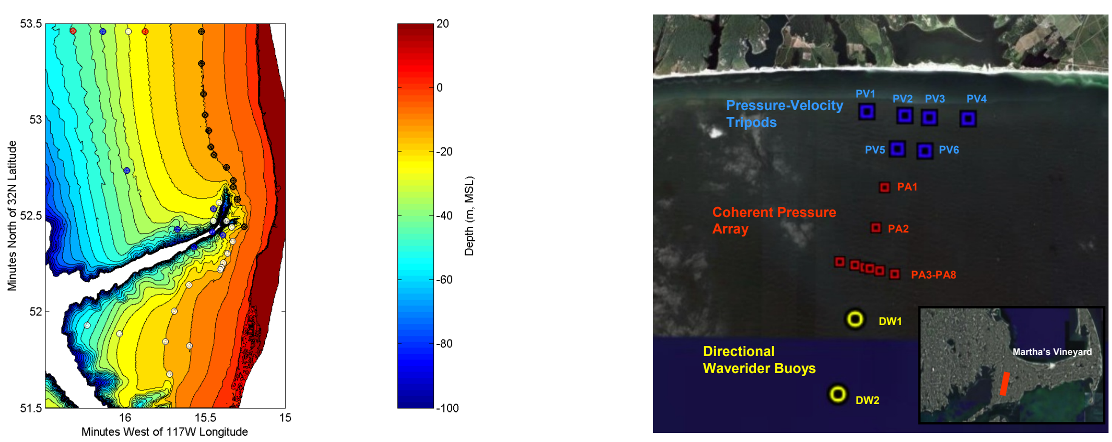

Figure 1 Left panel: Plan view of instruments (circles) deployed during September 2003 near La Jolla, California, as part of the Nearshore Canyon Experiment (NCEX). The array includes directional wave buoys (blue), bottom pressure recorders (white), pressure and current meters (black) and current profilers (red). Right panel: Array plan Martha's Vineyard Experiment. Detailed measurements of surface wave evolution across the inner shelf were collected during September and October of 2007. The array spans about 5 km from 24- to 8-m depth.

The dataset collected during the 2007 Martha's Vineyard Experiment, funded by the ONR Ripples DRI, is made available through our data site to the NOPP team. This experiment focused on the development and evolution of seafloor ripples excited by the orbital motion of ocean surface waves. The array of instruments during this experiment covers the inner continental shelf, with depths ranging from 8- to 24-m depth (see Figure 1), and includes areas of inhomogeneous sediment patches. This data set will provide a useful validation for bottom friction effects in heterogeneous sediment environments.

The Louisiana Waves-over-Mud MURI experimental data have been extensively analyzed (see Engelstad et al, 2012) and made available to the NOPP team. This dataset (Figure 2) provides a comprehensive set of observations of wave propagation across a muddy shelf that we used to validate wave-bottom interaction parameterizations over a mud-covered sea floor (Engelstad et al. 2012). This is an excellent data set to validate wave-bottom interaction parameterizations over a mud-covered inner shelf.

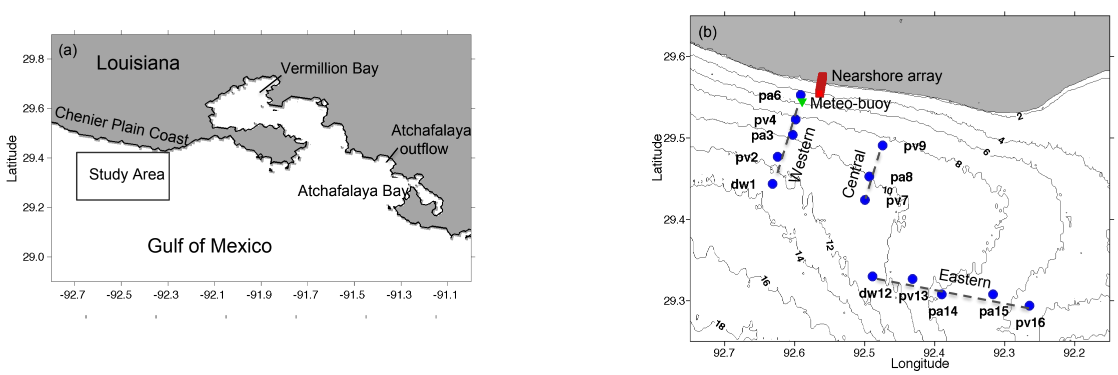

Figure 2 Overview of experimental area (left panel) and sensor locations (right panel, in blue) for the 2008 Louisiana Waves-over-Mud MURI experiment.

Testing of a one-point closure shallow-water model

We have completed testing of a one-point closure approximation in a shallow-water wave model against laboratory observations and Monte-Carlo simulations. The purpose of these tests is to explore the validity of this efficient alternative for shallow-water wave modeling.

Testing of a benchmark non-hydrostatic wave model

To develop a benchmark model for further validation of the shallow-water closure we have implemented and tested a non-hydrostatic model (SWASH) to capture nonlinear wave propagation in a dissipative surf zone. Non-hydrostatic models provide an efficient means to model nonlinear wave propagation. Our testes were aimed to study the representation of nonlinear dynamics in breaking waves (see Figure 3).

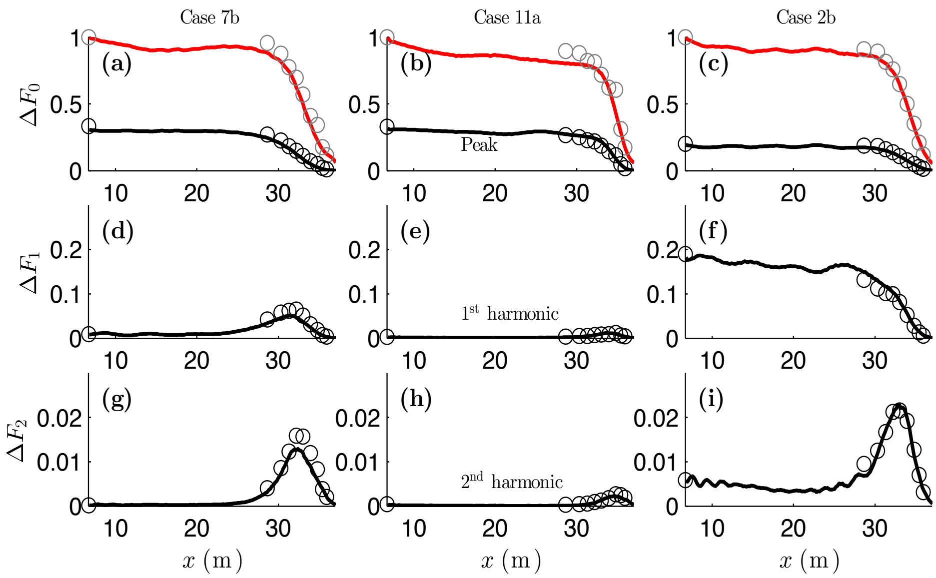

Figure 3 Comparison between the observed (symbols) and computed (lines) energy flux contained in a frequency band around the peak (panels a--c), the first harmonic (panels d--f) and the second harmonic (panels g--i). Each column represents a different case (indicated on top). In the upper panels (a--c) the normalized total flux is included (red lines/symbols) for reference.

Transport equations for wave correlators

We have developed a quasi-coherent (QC) theory for the transport of cross-correlations in random wave fields. These correlations are essential to model inhomogeneous and non-Gaussian effects in natural wave fields. We have studied the effects of two-wave correlators in focusing wave fields and in regions of diffraction. This work forms the basis for a new, isotropic description for the evolution of linear and nonlinear wave statistics that includes inhomogeneous wave fields, but is compatible with the action balance generally used in operational wave models.

Testing of radiative transfer equation in wave focal zone

Our findings in developing the QC theory suggest that the radiative transfer equation, which is standard in operational wave models, does not perform well in describing focusing of coherent waves. To test this performance we have implemented a SWAN model for the Columbia River mouth (see Figure 4), and compared model hindcasts with recent observations (see Figure 4). The comparisons indicate that the spatial variability of wave energy in the model is spread out over too large a region, and that the peak amplification is underestimated. This appears to confirm that the use of a geometric optics approximation is problematic in such high-energy focal regions (see Smit & Janssen, 2013a). Other factors that could play a role include errors in model representation of wave dissipation, and wave-current interaction.

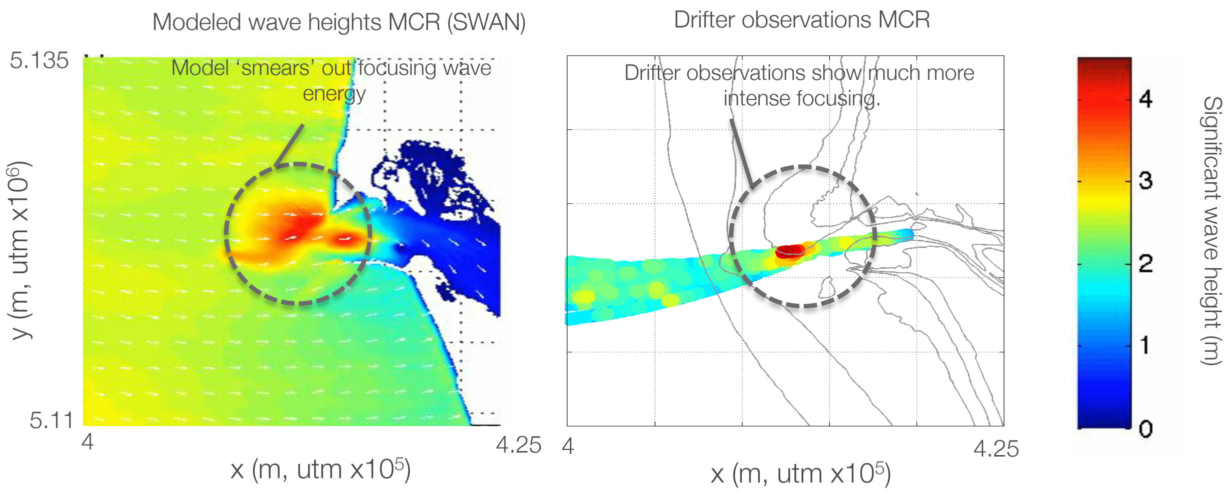

Figure 4 Comparison between modeled wave heights (SWAN) and drifter observations in the Mouth of the Columbia River for June 8 2013. The observed and modeled wave focusing near the Columbia river bar show considerable differences. The SWAN model uses observations from CDIP buoy # 46248 as boundary condition; three-dimensional current data and bathymetry is provided by the Center for Coastal Margin Observation and Prediction (CMOP).

RESULTS

Non-hydrostatic modeling of nonlinear waves through a dissipative surfzone

To develop a benchmark to test stochastic closure models, we have tested the performance of a non-hydrostatic model for simulation of nonlinear wave propagation through a dissipative surfzone (see Smit et al. 2013b). Despite the simplifications inherent to this class of deterministic models (e.g. single-valued surface), the representation of both nonlinear and dissipative characteristics of the wave propagation is excellent (see Figures 5 and 6).

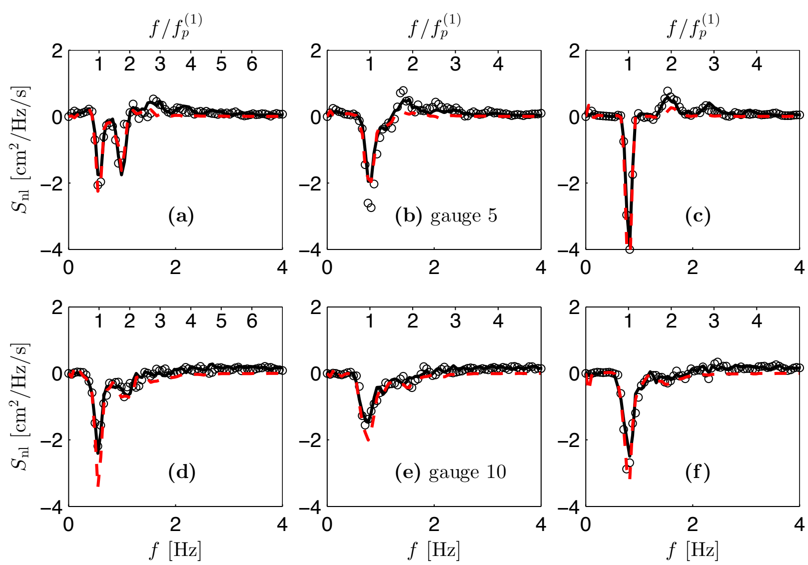

Figure 5 The non-linear source term S_{nl} computed from the bispectrum obtained from the observations (markers) and computations (solid black line), and the linear flux gradient (dashed red line) estimated from model results. The lower horizontal axis indicates the frequency, whereas the upper axis in each panel indicates the normalized (by the peak frequency) frequency.

Since non-hydrostatic models are relatively efficient, they can be used to simulate wave statistics through Monte Carlo simulations. The evolution of the surface elevation probability density was shown to be in excellent agreement with what was observed.

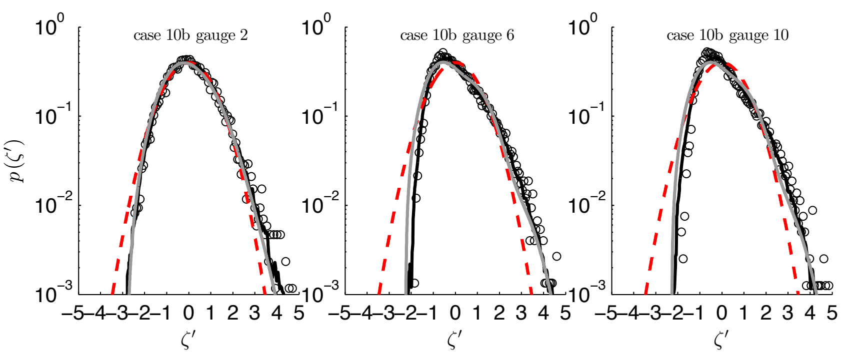

Figure 6 Shown is comparison for the observed (circles), modeled (solid black line), Gaussian (dashed red line), and two-term Gram-Charlier expansion (grey line) probability density function (pdf) for the normalized free surface elevation at various locations in the surfzone. The deviations from Gaussianity seen in the observations are accurately reproduced in the model, and in goo agreement with the Gram-Charlier expansion.

Overall, the non-hydrostatic model accurately captures the spectra, nonlinear transfers, bulk statistics, and complete nonlinear statistics for waves in a flume propagating onto a planar beach. The comparisons included a wide range of initial wave conditions with wave breaking mostly in the spilling breaker regime.

Transport equations for inhomogeneous wave fields

Comparison of simulations with the quasi-homogeneous wave theory developed by Smit & Janssen (2013a) highlights the shortcomings of the radiative transfer equation (RTE) and the improvements implied by the newly developed quasi-coherent (QC) model to capture wave focusing in a stochastic modeling framework (see Figure 7). The QC model captures wave interference patterns in a wave focal zone, which is expected to be important in coastal inlets, near headlands, and other coastal areas where refractive focusing occurs. This model is a first, and essential, step in developing fully two-dimensional bispectral evolution equations, which is presently ongoing.

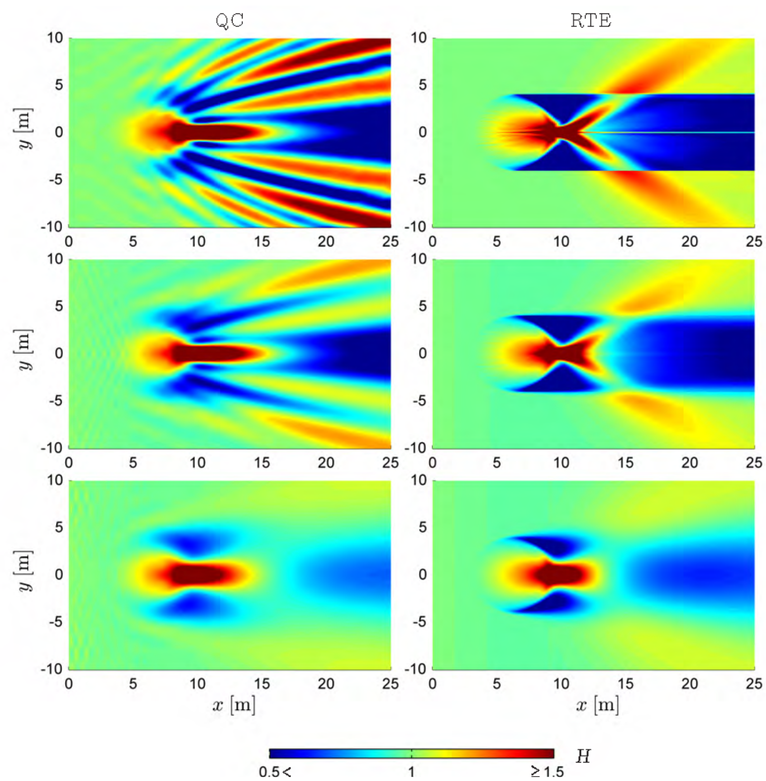

Figure 7 Plan view of modeled (normalized) wave heights for the experimental set-up as considered by Vincent & Briggs (1989) for case M2 (top panels), case N4 (lower panels) and the additional case N4' (middle panels) as considered in Smit & Janssen (2013a). Comparison between the QC model (left panels) and the RTE (right panels), shows that the QC approximation, in contrast to the RTE, resolves the fine-scale interference pattern in the focal zone of a topographical lens.

For narrow-band waves (swell) the quasi-coherent model and the standard radiative transfer equation (as used in most operational wave models) are at considerable variance (see Figure 8). This goes to illustrate the breakdown of geometric optics and the fact that in the vicinity of a caustic in a coherent wave field, the more general quasi-coherent (physical optics approximation) provides a much better approximation of the evolution of wave statistics.

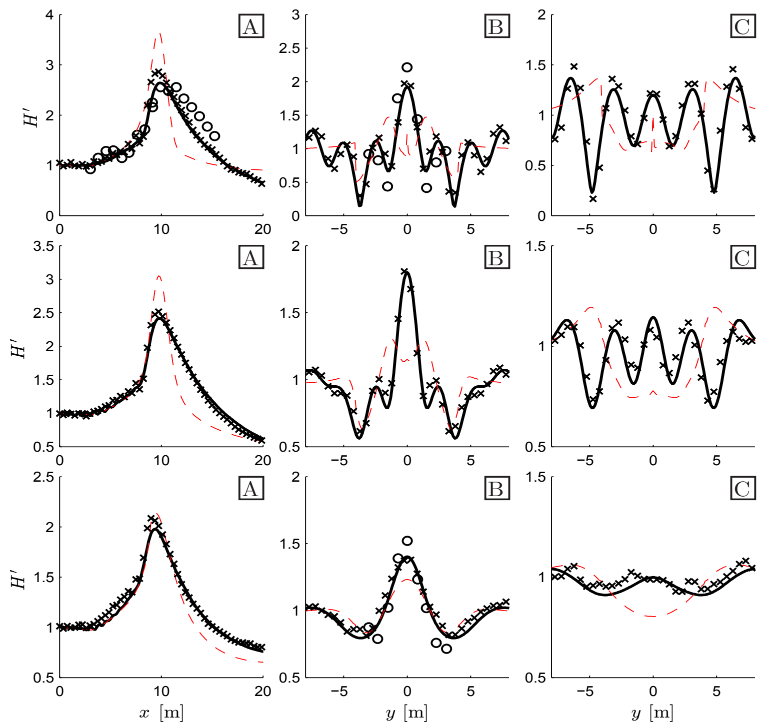

Figure 8 Shown are normalized wave heights along transects considered by Vincent and Briggs (1989) for case M2 (top panels), case N4 (lower panels) and the additional case N4' Middle panels) as considered in Smit & Janssen (2013a). Comparison is between the QC approximation (solid black line), observations (circle markers, when available), the deterministic model SWASH (crosses), and the RTE (dashed red line).

Statistics in a coastal wave focal zone

Recent observations of wave focusing over the Columbia river bar show that the observed spatial distribution of wave energy in the focal region is at considerable variance with SWAN hindcasts.

These results are preliminary, but they confirm the shortcomings of a geometric optics approximation for the prediction of wave statistics in a coherent wave focal zone, which appears consistent with the theoretical work developed in Smit & Janssen (2013a). Other factors (e.g. parameterization of wave dissipation) can be important also. We are currently working on better understanding these large differences between modeled and observed wave energy levels.

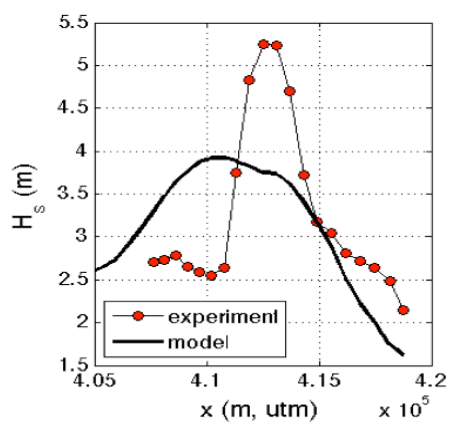

Figure 9 Comparison of observed (red markers) and modeled (black solid line) wave heights along drifter track. The model simulations were initialized with offshore buoy data. The bathymetry and current data were kindly provided by the Center for Coastal Margin Observation and Prediction (CMOP).

IMPACT/IMPLICATIONS

The model improvements developed and tested in this study will contribute to improvements in modeling capability of nearshore wave propagation in research and operational models. Efficient and accurate approximations for four-wave interactions will improve prediction of spectral shapes in operational models. The development of general evolution equations for wave correlators form a basis for the development of a new class of stochastic models that include inhomogeneous and non-Gaussian statistics. In turn, improved modeling capability of wave dissipation, spectral evolution, and higher-order statistics such as skewness and asymmetry, will contribute to improvements in research and modeling of coastal circulation and transport processes.

RELATED PROJECTS

The development of transport equations for cross-correlations in random waves also contributes to the study of coastal wave-current interaction as part of the ONR Inlets and River Mouths DRI.

REFERENCES

Boers, M. 1996; Simulation of a surf zone with a barred beach, part 1: Wave heights and wave breaking, *Comm. Hydr. Geotechn. Engn.* 96-5 Delft University of Technology, 116 pp.

Janssen, T. T., T.H.C. Herbers, and J. A. Battjes, 2006; Generalized evolution equations for nonlinear surface gravity waves over two-dimensional topography, *J. Fluid Mech.* **552**, 393-418.

Janssen, T.T. 2006; Nonlinear surface waves over topography, *PhD dissertation*, Delft University of Technology, 208p.

Smit P. B. and T. T. Janssen, 2013a; The evolution of inhomogeneous wave statistics through a variable medium, *J. Phys Ocean.* [in press, refereed]

Smit P. B., T. T. Janssen, L. H. Holthuijsen, and J. Smith, 2013b; Non-hydrostatic modeling of surfzone wave dynamics, *Coast Engn.* [in press, refereed]

Tolman, H.L., 2012; A Generalized Multiple Discrete Interaction Approximation for resonant four-wave nonlinear interactions in wind wave models with arbitrary depth. *Ocean Modelling* [submitted, refereed].

Van Vledder, G.Ph., 2001; Extension of the discrete interaction approximation for computing quadruplet wave-wave interactions in operational wave prediction models. *Proc. 4th ASCE Int. Symp. on Ocean Waves, Measurement and Analysis*, San Francisco, CA, USA..

Van Vledder, G.Ph., 2012; Efficient algorithms for non-linear four-wave interactions. *Proc. ECMWF Workshop on Ocean Waves*.

Vincent, C. L., and M. J. Briggs, 1989; Refraction–diffraction of irregular waves over a mound. *J. Waterw. Port Coastal Ocean Eng.*, **115**, 269–284.

PUBLICATIONS

Engelstad, A., T.T. Janssen, T.H.C. Herbers, G. Ph. Van Vledder, S. Elgar, B. Raubenheimer, L.T. Trainor, and A. Garcia-Garcia, 2012; Wave evolution across the Louisiana shelf, *Cont. Shelf Res.* **52**, 190-202. [published, refereed]

Pearman, D.W., T.H.C. Herbers, T.T. Janssen, S.F.McIntyre, P.F. Jessen, 2013; GPS and accelerometer equipped drifters for observing ocean surface waves and currents, *Cont. Shelf Res.* [in review, refereed]

Rogers, W.C., and G.Ph. van Vledder, 2013; Frequency width in predictions of windsea spectra and the role of the nonlinear solver. *Ocean Modeling*, **70**, 52-61 [published, refereed]

Smit P. and T. T. Janssen, 2013; The evolution of inhomogeneous wave statistics through a variable medium, *J. Phys. Ocean.*, **43**, 1741-1758. [published, refereed]

Smit P. B., T. T. Janssen, L. H. Holthuijsen, and J. Smith, 2013b; Non-hydrostatic modeling of surfzone wave dynamics, *Coast Engn.* [in press, refereed]